International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 6 Issue 5, July-August 2022 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

To Design Extrusion Mechanism and Mix for 3D Concrete Printing

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ABSTRACT

Additive Manufacturing (AM) or 3D concrete printing (3DCP) is a state-of-art method where layer- by-layer structural members are rapidly constructed with automatic machine control and that commit to be notable benefits in the field of construction in terms of design flexibility, Diminished construction cost, time, manpower and construction waste. So 3DCP has vital importance to overcome the housing crisis in many regions and reduced pollution due to construction activities. In this study, an effort has been made to modify FDM based 3D printer into a 3D concrete printing by the modification of the extrusion mechanism. Most of the equipment's which are used in modifying the printer are 3D printed. 3D concrete printed components are generally less dense and porous so grey micro silica fume is added in the cement as a micro filling material along with fly ash for the extrusion of a mix. Conventional mortar or concrete is not feasible material for printing, due to several issues i.e. printer's nozzle blocked by aggregate, naturally so-called brittle nature of concrete attributes relatively low tensile strength thus at risk of cracking, a problem occurs in compaction and layer-by-layer issues during placement, These issues overcome by insertion of micro-materials into the matrix of cement. Micro-materials such micro silica fume have ultra-fine particles in approximately 100 thousand particles per cement will fill the water gaps with fresh mortar. This micro filling effect significantly reduces penetration and improves the binding of mortar compared to conventional mortar. Silica fume responds quickly to provide high initial strength and durability. The efficiency of the silica fume is 3-5 times the OPC and as a result, the performance of the concrete or mortar can be greatly improved. It's expected that the study of this topic may be a milestone for the blueprint of bigger-scale projects in the future.

KEYWORDS: *3D concrete printing; Additive manufacturing; grey silica fume; concrete printing; buildability; extrudability*

How to cite this paper: Antariksh Joshi | Dr. A. K. Jha | Dr. R. S. Parihar "To Design Extrusion Mechanism and Mix for 3D Concrete Printing" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-6 | Issue-5, August 2022, pp.1771-1778, URL: www.ijtsrd.com/papers/ijtsrd51767.pdf

IJTSRD51767

I. INTRODUCTION

The construction industry is most vital to promoting the economic development of any country. Onthe other hand, traditional construction faces lots of issues, primarily concerning speed and low labor efficiency, many hurdles have to be faced to be overlooked to keep the construction site under control, physical labor participation causes a lot of health-related problems to the worker [OSHA US department]. Projects in the construction sector take a lot of time, so slow progress of project completion is the main obstacle in the construction sector. Environmental pollution and carbon emission are increasing rapidly due to the construction sector.

Most of the issues of the traditional construction sector can be solved by 3D concrete printing (3DCP). The main edge of 3DCP is the speed at which structure or part of the structure can be rapidly built compared to the traditional construction method as well as project completion time is reduced 60% to 80% and 60% less waste engendered during 3D printing compared to the traditional construction method (Guangchao Ji et al. 2019). Complex designs can be printed in a few hours or days. 3DCP reduces a lot of steps into a few. 3D printer would directly build the structure using Raw material as per the design of the CAD model. 3DCP is a low labor cost method

and if it is used in building structures on a large-scale, then it will be ample cost-effective compared to traditional construction. 3D printing offers the designer immense freedom to create very complex geometrical shapes and allows absolute customization of design. The traditional method of construction generates a high volume of waste material, which adversely affects the environment and human health. In 3D concrete printing, generally, the material is required only to build a structure. As a result, a very small amountof waste is produced in this method, so it would have very little negative effects on the environment, thus this reduces carbon emissions and clean the environment and also encourage a sustainable development structure. If 3D printing is compared with the traditional construction sector at these points such as "Speed, customization, design freedom, cost, sustainability, quality, risk alleviation, manufacturing steps", so the same result will be obtained from this comparison that 3D printing is superior.

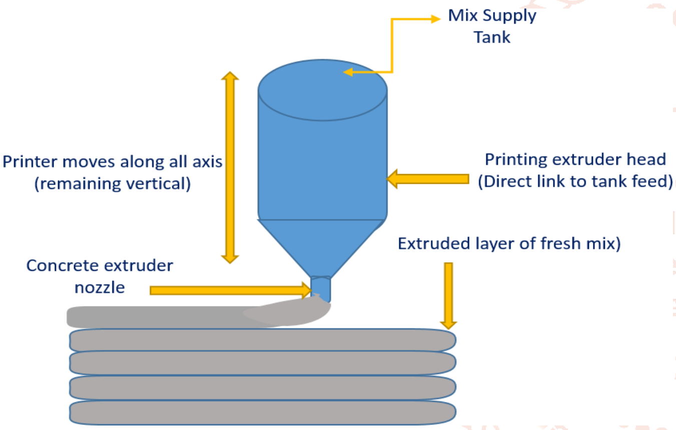


Figure 1: Principle of 3D Concrete Printing

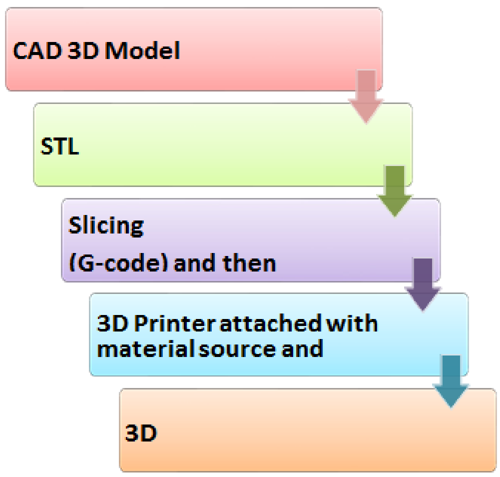


Figure 2: 3D printing process

II. LITRATURE REVIEW:

There is various researcher found out that Traditional construction methods are having a lot of adverse issues regarding speed, design flexibility, construction waste, manpower, environmental pollution. Automation in construction mostly resolves all these concerns. Additive manufacturing (AM) or 3D concrete printing is a novel automatic machine-controlled method ofconstruction to overcome most of the drawbacks of the traditional construction method. This chapter primarily focuses on precisely screening the literature survey done by numerous researchers from several standard journals. The review contracts with the several available journals in relevant areas of the research to examine the problem recognition of the currentwork. The core objective of the review is to accumulate relevant knowledge for additional implementation.

Allouzi et al. (2020) examine the comparative study between 3D printing and conventional construction on the point of material cost. This research article also targets to the considerate of procedure of 3-D printing, it's mechanism as well as impact through environmental, economic, and structural consideration is accomplished on the upcoming of construction. In this article, Rawan Allouzi compares the traditional construction info of Ras Alain versatile Hall (Jordan) in addition to predictable information if this similar structure would have been built with using 3DCP. The construction cost of Ras Alain Hall by using 3DCP is equaled to 8,872.5 JD (Jordan Dollar) deprived of the insulation work and stone cladding, and construction amount of the same hall by using traditional construction method is 57,947 JD if insulation work and stone cladding is excluded then construction cost is around 26,287 JD. So by this evidence of Rawan Allouzi, the concrete cost of Ras Alain Hall based on 3DCP is 8,872.5 JD is fewer than the traditional cost of construction which around 26,287 JD. The study concludes 3DCP diminishes 65% of traditional material costs. The labor costs, equipment cost, and construction time is not considered in this study meanwhile these factors depend on the speed and essential size of a 3-D concrete printer.

Khan (2020) this is a review work done by Mr. M. A. Khan which aims at reviewing suitable concrete 3D printed mix. From the study of different researchers following observations are drawn- There is a formation of Lubrication layer in the pipe due to segregation of concrete while pumping the mix because of that less pumping pressure is required. The flow ability of concreteis governed by particle size distributions of binder and sand grains. The suitable range of size of fine aggregate is in between 1mm – 2mm. For a mix having low yield stress and dynamic viscosity are helpful in pumpabilty of concrete nut for that same mix there is a problem observed in achieving Buildability. There is higher yield stress is observed for a mix having continuous gradation of material. Printable ranges of Plastic viscosity varies between 16.65 to 33.1 Pa-s and Static yield stress within 1.87 to 3.35 kPa.

Mechtcherinea et al. (2020) There are 3 main phases of extrusion-based 3DCP recognized as: i) extrusion of solid material, such as conventional extrusion, ii) extrusion of flowable mix with or without adding of non-binding composites (admixtures) in the print head, and iii) extrusion of materials using electrical input, two main methods failures are defined as the failure of an object during production, both of which are important in the construction of: i) the failure of the material, where the strength of the material is exceeded, and ii) the failure of stability due to loss of balance of power and time. Value simulation can contribute significantly to the analysis of flow processes under the consideration of complex geometric parameters; this has the capability to be developed into an influential design tool in modeling the 3DCP processes.

Panda (2019) evaluated the material fresh properties and process parameters on Buildability and Interlayer adhesion of 3D printed concrete. In this research work, he has prepared 2 mixes named control mix (CM) and mix with nano clay (NM). The control mix consists of following components 30% OPC cement , 67.5% Fine aggregate and 2.5% micro silica with the water/cement = 0.35 . The NM mix consists of nano clay particles 0.5% by weight of binder material in the CM mix. From the different observations, it was found that the NM mix has significantly higher buildability than the CM mix, The NM mix has higher yield strength than the CM mix, the nano clay particle can be used to increase the thixotropy of the mix, and Lower standoff distance is found use full for increasing the interlayer bond strength.

Craveiro et al. (2019) studied that the digital revolution of the construction area, mainly the perspective of additive manufacturing in building construction as a most significant technology of construction 4.0. The author clears the concept of construction 4.0 and also discussed as well as presented the digital makeover of the construction segment, however, Flávio Craveiro examines additive manufacturing for the construction purpose that permitting engineers and architects to design complex geometries. The author also stated the prime challenges in 3DCP from the viewpoint of fabrication such as to avoid clogs and premature solidification inside the 3D printer, printing time must be reduced. Furthermore, the collision of various-print heads or various robots/gantry systems must be avoided in the case of multiple material depositions, and also the printing of roofs (non-supported structure) or void (doorways, windows, etc.) is quite a huge challenge. To enhance the structural security as well as reliability innovative materials could be established predominantly by means of reinforcement (fiber meshes, fibers, steel, etc.), smart materials likewise self-healing, and shape-memory materials. However research on this topic concludes functionally and lightweight grouped structure, different materials used in additive manufacturing for construction, Flávio Craveiro also presents various research challenges and different processes of printing (Extrusion-based process, Jetting process, Fusion of inflated melting point materials. **Baz et al. (2019)** this research work is carried out to determine the effect of printing method and mortars workability on pull-out strength of 3D printed specimen. There are four different printable mixes are used in this research to find out the compressive and pull-out strength of the 3D printed specimen. For each mix, there are four different methods to place reinforcement in it. The first method of placing reinforcement is printing the concrete mix all around the bar in a circular manner, this method is called PerpM-1. The second method consists of placing two adjacent layers simultaneously using two guns, this method is called PerpM-2. The third method consists of using two guns at the same time along/parallel to the reinforcement, this method is called ParaM-1. The fourth method consists of placing one layer then inserting the reinforcement bar along with the layer such that half diameter of the bar inserted under the layer and over which the second layer is laid, this method is called ParaM-2. All these 4 samples are also compared with non-printed samples for compressive and pull-out strength. The key findings of this research work are- Printed samples act more homogeneously when mortar of higher workability is used, for compressive strength test perpendicular specimen always show lower strength than a non-printed specimen, The Pull-out strength of printed and non-printed samples are found to be almost same, PerpM-1 and ParaM-2 were the most qualified printing methods.

III. EXPERIMENTAL PROGRAM:

In this Chapter, the procedure of Designing, slicing, and printing of component which is used in the modified 3D concrete printer is discussed and also know about the general process of 3D printing such as making CAD solid model then after .STL file furthermore converts to gcode by slicing software. Along with the characterization of materials used and tests practice have been done and discussed. The properties and specifications of the materials, the mixture quantities, and proportions casting, and curing of the test sample are studied. XRD, RAMAN, SEM were used to study the microstructure of the materials. The focus of this experimental exploration is to check the feasibility of a modified 3D printer and find the optimum mix which is suitable for 3D printing.

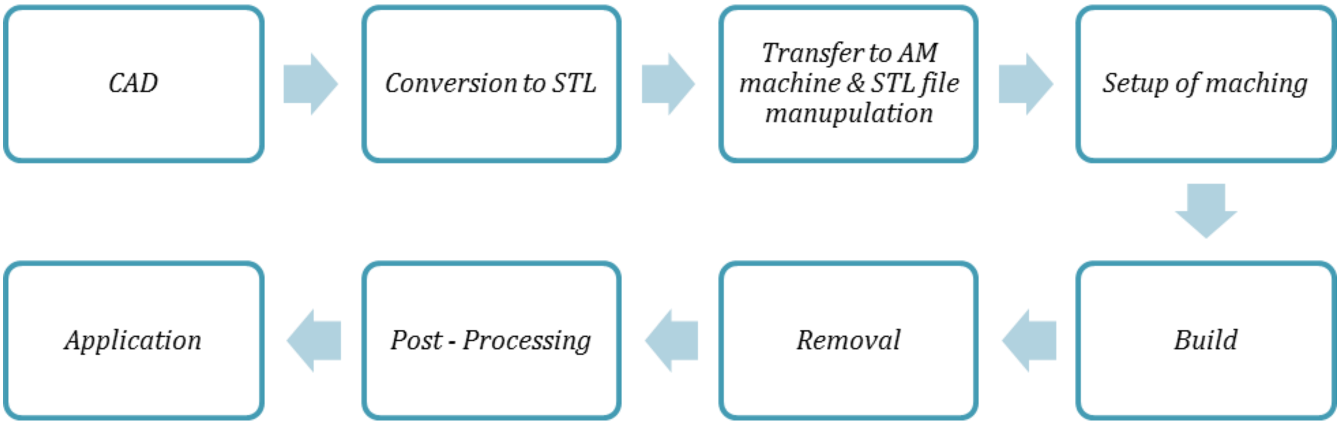


Figure 3: General process of Additive Manufacturing/3D printing.

Designing is not only the initial but also a crucial step of AM. Any object that is to be printedcan be easily visualized with the help of CAD and its converse is also true that any model that can be designed using a CAD such that it follows the laws of natural feasible designing can be 3-D printed. There are many computer software that can be used for the designing purpose and all have their own benefits and drawbacks. Some software is suitable for mechanical designing, some for animated or abstract aesthetical models while some are good for prototyping. But this does not mean that a particular software serves a designated purpose. If some factors related to machine configurations are kept in mind and enough attention is given to the details of the design every software will produce the same 3-D print. Still, it will be better to choose a software that could export the design in a file format that will be supported by the slicing software or you can choose a corresponding slicing software. What is required is that the file produced by the slicer should be supported by the printing machine and accordingly, the file produced by the design software should be supported by the slicing software. Some of the widely used design software are- CATIA, GEOMAGIC DESIGN X, AutoCAD, Blender, 3DXpert, Civil 3D, Corel CAD, Fusion 360, Paint 3D, GeoGebra Classic, Inventor, MATLAB, Meshmixer.

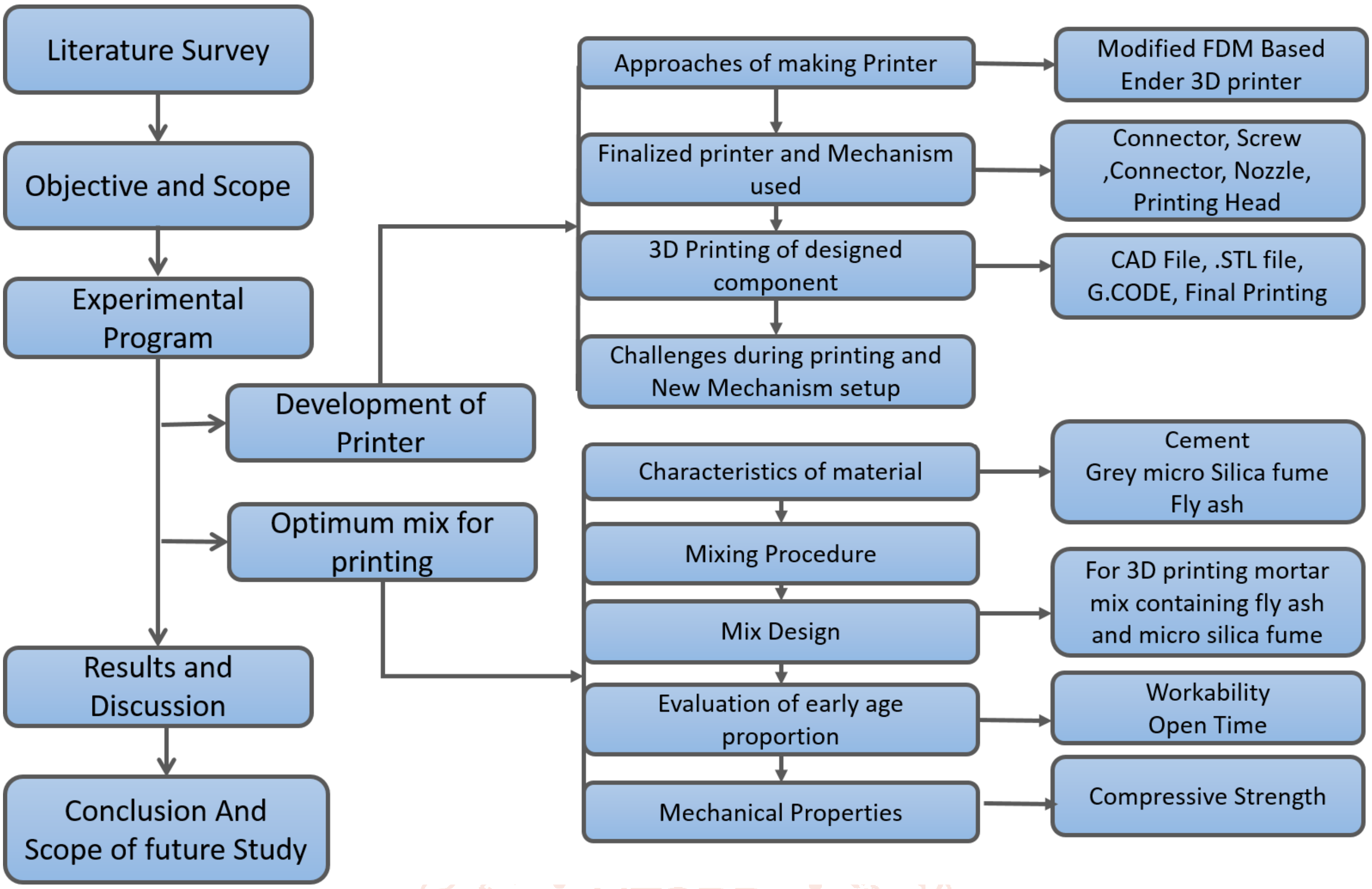
	Cement (g)	Sand (g)	Micro grey silica fume (g)	Flyash	Water/binder ratio	SP (g)
1.	2000	3000	0	857	0.3	10
2.	2000	3000	143	714	0.3	15
3.	2000	3000	286	571	0.3	20
4.	2000	3000	571	286	0.3	25
5.	2000	3000	714	143	0.3	30
6.	2000	3000	857	0	0.3	40

Table 1: Mix Design

The 3D Print add-on shows the following types of error in the design-
- Overhang face
- Non manifold edges
- Intersect face
- Zero faces
- Zero edges
- Non-flat faces
- Thin faces

IV. METHODOLOGY:

In this dissertation, the author will work on the 3D printing technique by giving proof of the concept of a modified 3D printer suitable for extrusion of cementitious mix or mortar. Also, check the feasibility of 3D printers and various challenges facing during printing. The study is done in this thesis is mainly focused on two things. First is the development of printer and additionally finding the optimum mix. 3D printed materials are generally less dense, so grey micro silica fume is also used in the mix as a micro filler material. The methodology has been done in the following steps as shown in sections 3.2, 3.3, or the flowchart.



Flow Chart Diagram of the Planned Study

Material aspects of 3D printable concrete

A. Printable concrete material constituents

Micro silica fume, fly ash, OPC, and sand was stocked or reserved at moisture free location or lab. These materials are used in for finding the optimum mix which is suitable for 3D printing.

B. Characteristics of Material

After material constituents, characterization of materials will be done in this dissertation, and XRD, RAMAN, and scanning electron microscope (SEM) were used to analysis of the microstructure of the different materials, and particle size distribution of fly ash is evaluated.

C. Mixing procedure

A fresh mortar mix of the desired quantity has been prepared for the direct compressive strength testing (DCT) experiments. Each constituent of the mix has been measured precisely on a digital scale and after that, they were further added for the mixingprocess. The amount of super-plasticizer, silica-fumes, and Fly-ash are varied in every mix however the water/binder ratio of 0.3 is always kept constant for every mix. The binder comprises of cement + fly-ash + silica fumes.

V. RESULT AND DISCUSSION

The results and observations obtained from the specified tests stated are presented and discussedin this chapter. extrudability, flow ability of 3D printable mix are discussed. The grey micro silica fume and fly ash containing mix were categorized by the concentration of grey micro silica fume and fly ash and also by ratio of sand/cement or binder. These mix samples were examined to obtain the properties includes workability, compressive strength, and open time at different ages. The results are being studied and have been concluded for the development of extrusion mechanism and the mix.

While performing the experiment of extrusion of mortar mix on the modified FDM based 3D printer, it was found that the printer has successfully printed a line of mortar mix onto the printing bed, but after printing one line, the connector of extrusion mechanism has been broken into two pieces from the outlet end of the connector because the cross-section area of the connector is reducing suddenly which will cause two problems during the extrusion of the mix,

Due to the sudden reduction in the cross-section area of the connector, lesser will be the area available for the extrusion of the mortar paste and high friction will be offered to the mortarby the walls of the connector because

of that frictional force segregation of the materials will take place and the problem of chocking is observed while performing the experiment.

Due to the presence of high frictional force on the mortar, it will not be able to move in the forward direction with the desired speed while at the same time continuous supply of the mortar is given at the inlet of the casing, due to that high pressure will be exerted by the materialover the walls of the connector, especially to the end having lesser cross-section area and the connector was not able to sustain that pressure and breaks into two pieces from the outlet end.

Flow ability means it is the ability to flow, in the case of 3D concrete printing flow ability means the ability to flow from pipes that are being used to transport the mix from the hopper section to the nozzle section. In this dissertation, the author finds that for 3D concrete printing mix must besignificantly flow able and Flow ability is also the function of workability. Flow ability increaseswith an increase in the water content of the liquid.

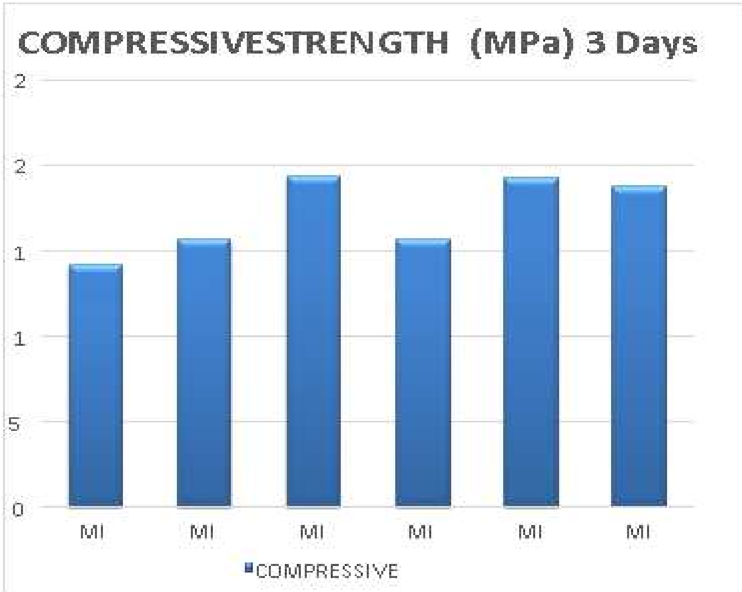


Figure 4: Compressive strength in 3 days

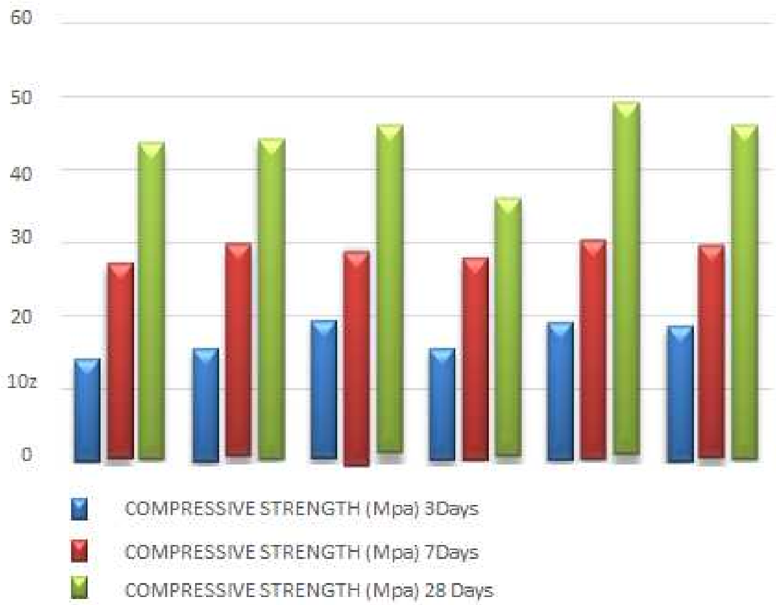


Fig 5 Variation in the strength of concrete while using Micro-Silica

VI. CONCLUSION:

On the basis of above experimental research and study of the results, following conclusions can be drawn.

The study concluded that 3D concrete printing is the process of layer-by-layer deposition for purpose of converting a designed digital model (CAD file → Mesh file → .stl file → 3D printed component) into the desired structure.

The reduction in the area provided in the extrusion mechanism must be gradual in nature. The sudden reduction in the area will exhibit high force on that particular section and may break the continuity of the

assembly by breaking that particular component of the mechanism.

3D printed PLA-based extrusion mechanism is not able to sustain the pressure applied bythe mortar mix because of the lower bond strength of 3D printed specimen between successive layers hence metal assembly must be adopted for the extrusion mechanism.

The power required to push the material in the forward direction is high and the required power for pushing the mortar will be equal to the weight of mortar in the assembly and total friction offered by the walls of the assembly. It is of prime importance to optimize the mix for extrusion without bleeding/segregating or setting in hose pipe and sustain theself-load for a considerable amount of time after deposition with accelerated hardening.

Silica Fume is exceptionally fine, the micro filling effect of silica fume significantly improves the binding of mix and provides more initial strength compared to conventionalmortar. The efficiency of the silica fume is 3-5 times the OPC. However, from the aspect of the extrudable mix, the following proportion used in mix - Cement– 70%, fly-ash– 20%, Silica fumes– 10%, sand: cement– 3:2, water: binder– 0.3, Superplasticizer– 0.5%.

Hence it can be concluded that the mechanism adopted in this dissertation is appropriate for 3D printing of mix. But more effort is needed on the design and strength of components used in the extrusion mechanism of 3D printer.

SCOPE FOR FURTHER STUDY

This study aims to build the foundation for further research that will enable the development of 3D printing in the construction sector.

Work on extrudability of the mix was performed and it was observed that lots of research are needed on the build ability aspect of the mix.

Many research groups and institutions are engaged in making a 3D printer for the construction industry. In the future, research will mainly focus on the development of 3Dconcrete printer using robots. 3D printers such as robots arm based printers may be very transportable, which will allow for more complex structures.

Much needs to be done before 3DCP technology is marketed, but the main and most challenging part of civil engineering lies in its management and maintenance of the quality of printed structure. Examples included feasibility studies, optimization of the material mix through cement replacement or partially adding nano or micro-substances to the binder.

The future of the 3D printing of infrastructure seems to be brighter. However, work on mix material capable of in-situ layer by layer deposition needs to be relooked. A movable and light-weighted printer will be needed to be developed for wider acceptability.

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